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Signature of Electric Fields from High and Low Altitude Particle Distributions

Space Sciences Laboratory
The Ivan A. Getting Laboratories
The Aerospace Corporation
El Segundo, Calif. 90245

23 August 1977

Interim Report

Prepared for
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Los Angeles Air Force Station
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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Measurements of high altitude ($<1.3\ R_e$) ions and electrons at auroral energies are used to provide evidence of parallel electric field acceleration over the dusk to midnight auroral regions for both the north and south hemispheres. The data, taken on August 12, 1976 by charged particle spectrometers on the S3-3 satellite, show evidence of potential differences of ~2 kV below and ~1 kV above a satellite altitude of 7300 km.

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PREFACE

We wish to thank the large number of people at The Aerospace Corporation and the Air Force who made the S3-3 program successful. The following people at Aerospace Space Sciences Laboratory offered valuable assistance: Dr. A. L. Vampola, for the use of his energetic particle data, Drs. Y. T. Chiu and Michael Schulz for many discussions concerning their electric field model, D. R. Croley, Jr. and G. M. Boyd for their assistance in the data reduction and presentation, and Dr. H. H. Hilton for the ephemeris and attitude calculations.

We also thank our co-experimenters on the S3-3 satellite: Dr. R. G. Johnson for providing the energetic ion mass spectrometer data, and Drs. R. B. Torbert and F. S. Mozer for the electric field data.

CONTENTS

FIGURES

Introduction

The study of the coupling between the magnetosphere and the ionosphere remains one of the most actively pursued subjects in space sciences. In the auroral regions, electric fields play a dominant role in the description of the dynamics of charged particles (Banks, 1975). One such result of the predicted parallel electric fields are the inverted 'V' structures widely discussed by Frank (1975), (Frank and Ackerson 1971, 1972), Gurnett (1972) and others (Reasoner and Chappell, 1973). Another signature of parallel electric fields that extend down to the ionosphere are ion beams accelerated to high altitudes (Shelley et al. 1976). The S3-3 satellite has provided evidence of strong electric fields which are ascribed as electrostatic shocks by Mozer et al., (1976).

The data presented in this letter, taken by the S3-3 satellite on August 12, 1976, provides convincing evidence of the acceleration of particles by electric fields parallel to $\underline{B}$ above and below a satellite altitude of 7300 km. For this particular event, a total potential difference of ~ 3 kV is inferred, 2/3 of which is located below the satellite.

Instrumentation

The data were obtained by two cylindrical electrostatic analyzers (ESAs) built by The Aerospace Corporation and flown on the polar orbiting satellite, S3-3. The nominal orbital parameters were: apogee of ~ 8040 km, perigee of ~ 240 km, inclination of 97.5°. The ESA's measured ions with energy to charge ratios in the range of 0.09 to 3.9 keV/q and electrons with energies of 0.17 to 8.4 keV in eight logarithmic steps. A complete ion and electron spectrum was taken every second and a complete angular distribution was measured every 20 sec. The geometric factors of 1.8×10^{-3} and 1.7×10^{-4} cm^2-ster-$\frac{\Delta E}{E}$ for the ions and electrons respectively give the instrument high sensitivity with low background signals. The angular fields of view were $\sim 7^{\circ} \times 10^{\circ}$ FWHM and $\sim 14^{\circ} \times 10^{\circ}$ FWHM for the electron and ion ESA respectively. Channeltrons were used as detectors with a post acceleration to 1.6 kV in the ion ESA. A companion instrument provides measurements of electrons and protons with energies from 0.012 to 1.6 MeV and 0.080 to 1.5 MeV respectively.

Presentation of Data

A summary of the low energy electrons and ions at high altitude is shown in Figure 1 for August 12, 1976. The top panel in the E-t spectrogram shows electrons with energies from ~ 0.17 to 33 keV along the vertical axis and universal time along the horizontal axis. The intensity (gray scale) is the differential energy flux in units of $[\mathrm{keV/cm^2\text{-}ster\text{-}sec\text{-}keV}]$. The bottom panel of Fig. 1 is for ions with E/q from ~ 0.09 to 3.9 keV. In addition to the low energy particles, the E-t diagram shows an electron differential channel at ~ 235 keV at the top and a proton integral channel at ~ 80 keV at the bottom. These latter two measurements are useful in estimating magnetospheric boundaries as intensity modulated bands. Parameters of satellite ephemerides are shown at the bottom and identify this data as a high altitude northern auroral pass near 1900 hours MLT.

The satellite completes a full angular revolution in approximately 20 seconds with the closest approach of the instrument's view axis around 6 degrees to the magnetic field. The electron 'trapping boundary', measured by 235 keV electons, is located near $\Lambda \simeq 69^\circ$. However, low intensity 235 keV fluxes extend to much higher latitudes ($\Lambda \geq 75^\circ$). The ring-current protons, identified by the 80 keV fluxes drop towards their threshold value near $\Lambda = 72^\circ$.

The data of primary interest occurs between 12100 and 12200 seconds U.T. where a series of intense narrow ion beams at pitch angles of 180° are observed coming from lower altitudes. These beams occur at invariant latitudes between 72.7° and 73.7°. Simultaneous with the ion beams, the electron energy fluxes at $E \sim 1$ keV show reduced intensities for pitch angles near 0° and 180°. These features and others discussed below are interpreted as follows: the reduced electron intensity is a result of a potential barrier

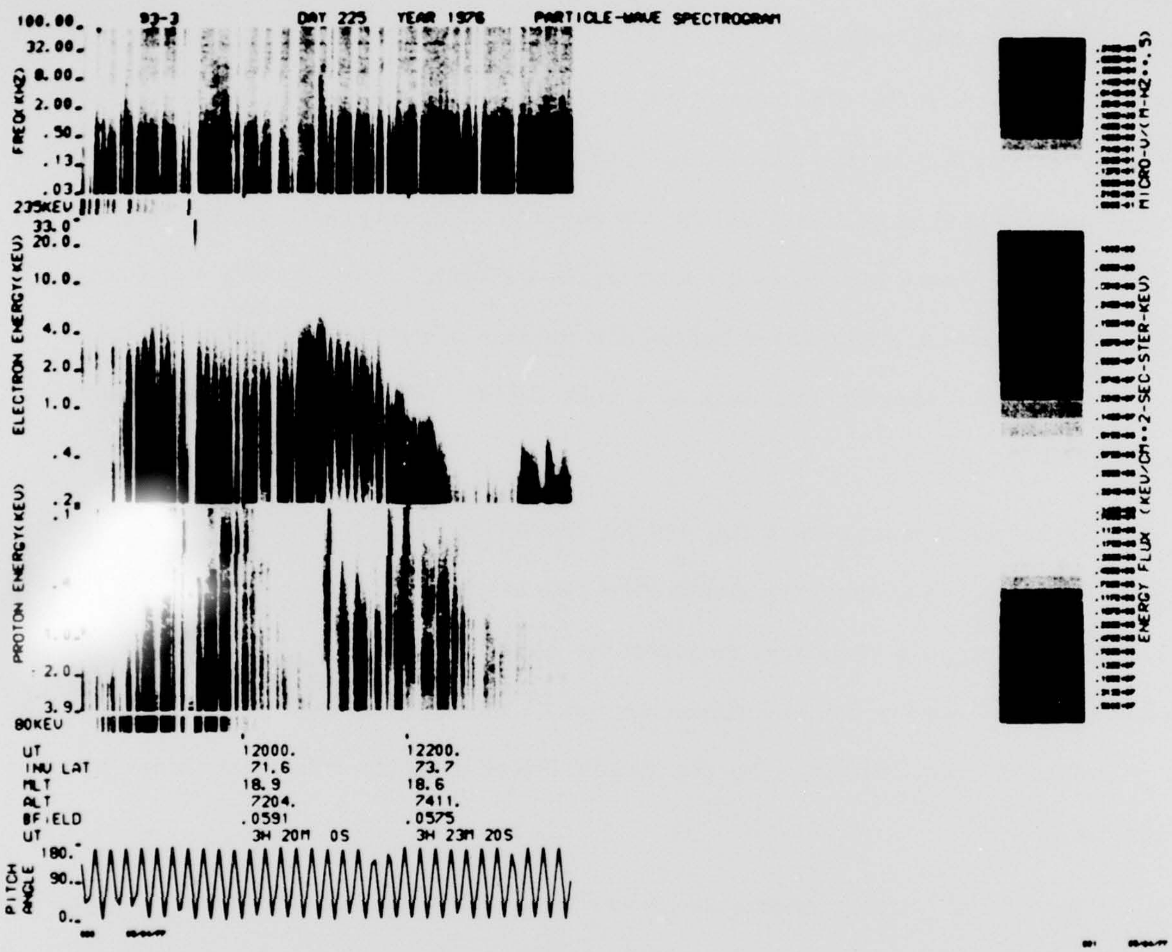

Figure 1. The Energy-Time Spectrogram for the North Auroral Data on Aug. 12, 1976. The low energy electrons are in the top half with energies from 0.17 to 33 keV increasing upward and the low energy protons (ions) range from 0.09 to 3.9 keV in the bottom half with energies increasing downward. There are two energetic differential energy channels shown; 235 keV electrons at the top, 80 keV protons at the bottom. The gray scale for the auroral particles ranges from $\sim 10^4$ to 10^6 and 10^5 to 10^7 [keV/cm^2-ster-sec-keV] for ions and electrons, respectively.

above the satellite while the ion beams are produced by an accelerating potential below. The result of such potentials would be manifested in an inverted 'V' structure at low altitudes.

A detailed look at the second ion beam distribution encountered is shown in Figure 2. The distribution function in velocity space is plotted for the time interval from 12111 to 12129 and shows the ion contours peaking at $-v_{\parallel} \simeq 600$ km/sec (i.e., $E \simeq 1.9$ keV). The term ion and proton can be interchangeable in our presentation because the ions are predominantly protons. This determination was made by the energetic ion mass spectrometer flown on S3-3 (R. G. Johnson, private communication). These data correspond to one full satellite rotation or ≈ 20 seconds. The units of the velocity are in km/sec and of the distribution function are in $sec^3 km^{-6}$. The angular half width of the ion beam centered at a pitch angle of 180^o is approximately $10\text{-}12^o$ wide at the 10% maximum intensity. The predicted nadir loss cone for the 100 km altitude is approximately 18.5^o, so the ion beams are located well inside the normal atmospheric loss cone.

The electron phase space densities are shown in the bottom of Figure 2 for the same time interval. At low electron velocities, perpendicular to $\underline{B}$, the distribution function shows a peak near 1.4×10^4 km/sec ($E \sim 0.6$ keV) with an intensity near 26 sec^3/km^6 (bounded by contour G). In Fig. 2 the phase space density is broad along the $v_{\perp}$ axis but narrows and goes to higher velocities along the $+v_{\parallel}$ axis. The dashed ellipse indicates the boundary between accelerated magnetospheric electrons and ionospheric electrons. The corresponding energy flux changes by over two orders of magnitude from the peak value at $E \simeq 1$ keV ($v_{\parallel} = 1.8 \times 10^4$ km/sec) down to $E \simeq 0.17$ keV ($v_{\parallel} = 0.8 \times 10^4$ km/sec) across this calculated boundary. This signature is strongly indicative of a parallel electric field acting to accelerate electrons down toward the earth. The distribution function for velocities less than 1.8×10^4 km/sec display the type of profiles one obtains by calculating

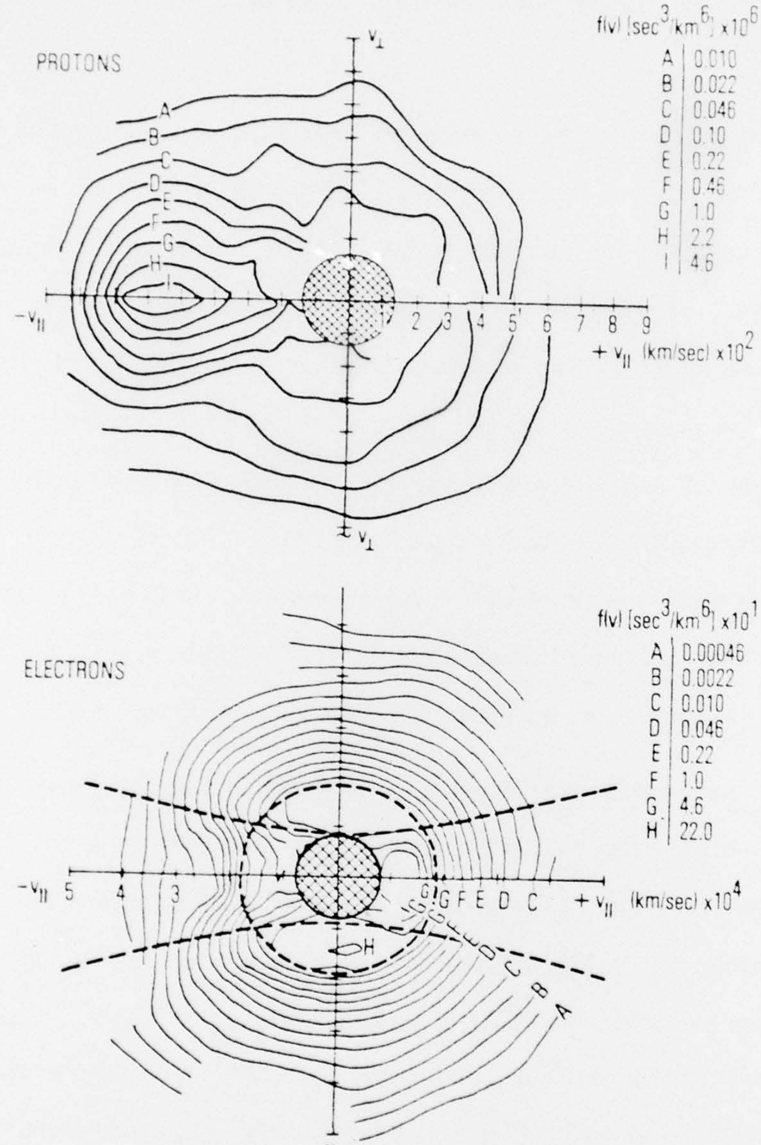

Figure 2. Distribution Function Contours of Protons and Electrons for UT = 12111 to 12129 Seconds on Aug. 12, 1976. The proton intensity ranges from $\sim 1 \times 10^4$ to 4.6×10^6 sec^3/km^6 for velocities from (1.3 to 8.6) $\times 10^2$ km/sec. The electron intensity ranges from $\sim$ 0.046 to 22 sec^3/km^6 for velocities from (7.7 to 54) $\times 10^3$ km/sec. The dashed curves are population boundaries derived from the formalism of Chiu and Schulz (1977) and fits to the data.

the boundaries in phase space that delineate different particle distributions in the presence of an electric field parallel to B (Chiu and Schulz, Fig. 1, 1977; Whipple, Fig. 6, 1977). For example, electrons within the atmospheric loss cone are bounded by the dashed hyperbola (Fig. 2) which has $v_\perp$ intercepts of:

$$\pm \{(2/m_e)|e|(V_T - V)/[(B_a/B)-1]\}^{1/2} \qquad (1)$$

The dashed ellipse which has $v_\parallel$ intercepts of:

$$\pm [(2/m_e)|e|V]^{1/2} \qquad (2)$$

V_T is the total potential drop down to the atmosphere, V is the potential at the satellite and B_a/B is the ratio of the magnetic field strengths which defines the loss cone pitch angle at the satellite. (Chiu and Schulz, 1977). From the f(v) contours in the $-v_\parallel$ quadrants in relation to the dashed curves in Fig. 2, one can see the nadir loss cones widen at the lowest velocities. For example, the local atmospheric loss cone at a satellite altitude of 7300 km is $\simeq 18.5^\circ$. A particle with a pitch angle greater than 162° will mirror below 100 km in altitude. The measured loss cones for the electrons at this time vary from $\approx 150^\circ$ to 120° as the velocity decreases from ~ 30 down to $\sim 0.8 \times 10^4$ km/sec. These enhanced loss cones are consistent with a parallel electric field below the satellite that accelerates the positive ions to approximately 2 keV.

The combination of the electron and the ion distribution functions clearly shows the existence of a strong potential drop along B above and below 7300 km. To obtain an estimate of this potential difference between the cold ionospheric ions below and the magnetospheric electrons above, differential energy spectra at 0°, 90° and 180° pitch

angle are presented. Figure 3 shows the differential energy flux spectra for these ions and electrons at high altitude. The top spectrum is for ions coming up from the earth at UT = 12120 sec. The peak intensity of $\sim 6 \times 10^7$ [kev/cm^2-ster-sec-kev] occurs at an energy near 2 keV. The spectrum changes by over three orders of magnitude from $\sim$0.1 to 2 keV. The second set of spectra, shown in Fig. 3 at high altitude, are for electrons; downgoing, upcoming and mirroring. The downgoing electrons have a peak flux of 7×10^7 [keV/cm^2-ster-sec-keV] near 1 keV.

The upcoming and downgoing electron fluxes are the same (within statistical errors) for energies below $\sim$1 keV. This feature of equal intensities for fluxes at 0° and 180° is characteristic of secondary or backscattered electrons in the presence of an inverted 'V' structure. It was pointed out by Evans (1974) and Whipple (1977) and shown experimentally by Mizera et al. (1976) that these types of distributions would occur if a parallel electric field above the observer were of sufficient strength to turn the backscattered electrons around. Therefore the interpretation of the downgoing and upcoming high altitude electron spectra in Fig. 3 is that a parallel electric field above 7300 km is an effective barrier that reflects upcoming electrons with energies less than 1 keV and results in the same intensity for the upcoming and downgoing fluxes at the satellite altitude.

The spectrum for the mirroring electrons at high altitude shows a low energy component that is not present in the downgoing electrons whereas the high energy component is virtually the same. The low energy electrons, with pitch angels near 90°, are also confined below the inferred potential barrier above the satellite. The mirroring spectrum in Fig. 3 indicates the existence of a significant trapped electron population at low energies between the top of the potential barrier and the atmosphere. In Fig. 2, this

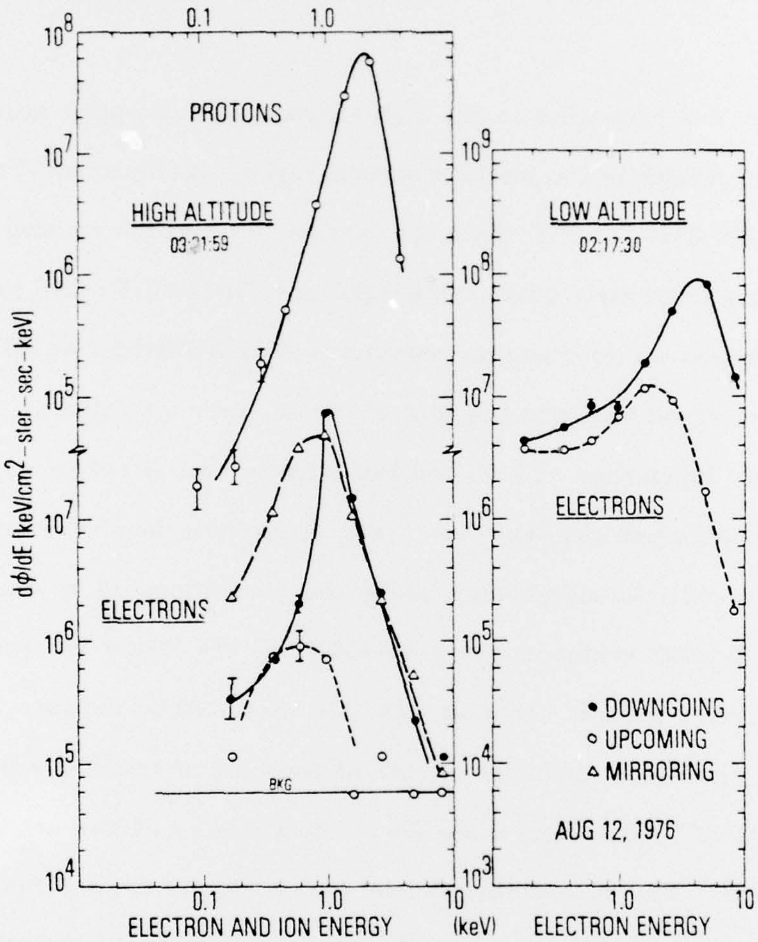

Figure 3. Differential Energy Flux Spectra for Protons and Electrons at 7300 km over the Northern Auroral Region and Electrons at 275 km over the Southern Auroral Region. These data were taken approximately one hour apart on Aug. 12, 1976 in the dusk to midnight local time sector. The background level is one count threshold.

trapped electron population is bounded by the dashed ellipse which has intercepts given by:

$$\pm \{[(2/m_e)|e|V]/[1-(B_o/B)]\}^{1/2} \tag{3}$$

B_o/B is the ratio of magnetic field strengths at the equator and the satellite (Chiu and Schulz, 1977).

Approximately one hour prior to the high altitude northern polar acquisition, data were also taken near perigee in the southern auroral region. An inverted 'V' structure was observed between 8220-8260 sec U.T. when the satellite crossed the evening auroral zone near 275 km. The magnetic field coordinates were $\Lambda = 70.6^o$; MLT = 23.2 hrs. From the characteristics of the ion and electron measurements at high altitude, we inferred that an inverted 'V' structure would locate at the foot of the northern field line at $\Lambda = 72.9^o$ and MLT = 18.6 hrs. This comparison of high and low altitude data is not to suggest that the same structure was observed one hour apart and in opposite hemispheres, but only to exhibit the charged particle morphology under the limitations of a single satellite's measurements. Additional evidence was gathered from the DMSP auroral photographs taken over the southern auroral zones around this time. They indicate a narrow arc structure extending from local midnight to dusk at the time of the S3-3 southern perigee data. On the next DMSP acquisition, some 100 minutes later, a narrow arc structure near dusk was also present. These measurements tend to corroborate the description of narrow inverted 'V' structures during the time of the S3-3 measurements at both apogee and perigee.

The low altitude inverted 'V' structure is characterized by the spectra shown in Figure 3. These electron data were taken near the peak of the inverted 'V' structure. The comparison of the upcoming with the downgoing fluxes in the loss cone is one of our

methods of identifying parallel electric field acceleration above the satellite (*Mizera et al.* 1976). Within experimental uncertainties, we would estimate the magnitude of the total potential drop over the southern auroral zone to lie between 2 and 3 kV. Our estimate of the total potential measured at high altitudes above the northern auroral region is obtained by summing the peak value of the ion beam spectrum ($\sim$2 keV) with the value obtained from the upcoming and downgoing electron spectra ($\sim$1 keV) or a total potential drop of $\approx$ 3 kV. It is perhaps a fortuitious circumstance that the potential difference along $\underline{B}$ inferred from the high and low altitude data agrees so well with each other. Nevertheless this may indicate a rather reproducible feature in the auroral morphology for the dusk to midnight local time sector.

Summary and Speculations

The data presented here represent one more piece of information added to the diversity of auroral measurements. It provides convincing evidence that substantial electric fields, parallel to **B**, are operating over both hemispheres at relatively low altitudes ($< 2\ R_E$). This example is just one of many similar observations made by the S3-3 satellite at altitudes between 6000 - 8000 km. We hesitate to use the word "typical" to describe this event, but the occurrence of upward streaming ions from the earth's dusk to midnight local time sector, in the few keV energy range, are common observations.

Spectra of accelerated ions parallel to **B** taken at altitudes above 6000 km have been observed at invariant latitudes as high as 87°. Our preliminary examination of these high latitude data during times of quiescent magnetic activity ($K_p \leq 2+$, $A_p \leq 12$), shows that the ions coming from the earth are observed over a range of local times. The very high latitude ion beams are generally associated with intense, soft electron precipitating fluxes. (The energy of these accelerated fluxes range up to ≈ 2 keV for electrons and ≈ 4 keV for ions.) The latitude extent of the individual accelerated fluxes vary from a few tenths of a degree to greater than five degrees.

Just as the ions provide an estimate of the potential drop below the satellite, the electrons can provide the magnitude of the potential drop above the satellite. From Figures 2 and 3, we can infer a 2 kV potential below 7300 km and 1 kV potential above. Therefore 2/3 of the parallel electric field resides below 7300 km. The total potential drop of ≈ 3 kV agrees well with that inferred from the low altitude electron data taken at the opposite hemisphere one hour earlier. Additional evidence of parallel electric fields is provided by the reduced intensity of the backscattered electrons in Figure 3 at high

altitude. This reduction would occur if the low altitude backscatter spectrum is shifted in energy by an amount equal to the potential drop below the satellite. The observation of the enhanced loss cones in the electron pitch angle distributions and the velocity space contours in Figure 2 are also consistent with a total potential difference of approximately 3 kV.

In principle, estimates of the location in altitude can be inferred from a careful examination of the auroral pitch angle distributions (Kaufmann et al., 1976). A preliminary examination of the electron pitch angle distributions showed that the loss cones of the lowest energy electrons (≈ 0.2 keV) were enhanced by approximately 40^{o} from the value near 162^{o} that is expected in the absence of an electric field acceleration. As the energy of the observed electron distributions increased up to ~ 2 keV, the atmospheric loss cone approached 160^{o} as predicted by the first adiabatic invariant relationship in the presence of a potential difference along $\underline{B}$. In order to estimate the location of the electric field, a detailed model of the ionospheric and atmospheric processes including the source region of the ions must be invoked. This procedure is beyond the scope of this analysis at this time.

However from the data analyzed and presented here, we can for the first time put limits on the parallel electric field associated with inverted 'V' structures. Since the total potential drop below 7300 km is approximately 2 kV and the distance between the ionospheric source and the satellite is approximately 6000 km, a lower limit of ≈ 0.3 mV/meter would be predicted for a uniform electric field. If we extend this value above the satellite to account for the 1 kV potential inferred from the high altitude electrons, then the electric field would terminate beyond $\simeq 10{,}000$ km. This estimate assumes that the potential drop above and below the satellite constitutes a single extensive structure. Using this assumption, a self-consistent solution for the electric field, in agreement with the particle data at both high and low altitudes, can be obtained in the model of Chiu and Schulz (1977).

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